Concurrent Object-Oriented Programming and Petri Nets, G. Agha & F. De Cindio (Eds)., Lecture Note in Computer Science 2001, 2001, Springer-Verlag.

CoOperative Objects: Principles, Use and Implementation

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Abstract. It is no longer relevant to praise the qualities of the Object-Oriented Approach and the Petri Net Theory. Each of them has proved to be a powerful framework in its field of application. However it is a challenge to associate them into a conceptual framework which combines the expressive power of both approaches while maintaining their respective merits. Moreover, it must be shown that such a formalism can be implemented in a sound and efficient manner.

This paper is a comprehensive presentation of the CoOperative Objects formalism. This formalism embraces the theoretical and pragmatic features of both the Petri net and the Object-Oriented approaches by thoroughly integrating their concepts. It is as well-adapted to the specification and the validation of open distributed systems as to their implementation. The basic idea is that a Petri net processes data objects as tokens, while the behaviour of an active object is defined by a Petri net. This paper also proposes a CoOperative Object solution to the dynamic dining philosophers problem, and tackles implementation issues through the presentation of SYROCO, a CoOperative Objects compiler.

I. Introduction

Petri nets (**PN**s) are one of the formal models of concurrency. They are successfully used to deal with concurrent discrete event systems and in particular with distributed systems such as operating or manufacturing systems, business or software development processes. They are applied to existing or planned systems for performing various tasks: requirements analysis, specification, design, test, simulation and formal analysis of the behaviour [ISO 97]. Projects concerning such systems most often lead to the development of software that either serves as a tool supporting the system's activities, or controls its behaviour, or constitutes its final implementation. In such casees, Petri nets are used only during the early steps of the project and not during the software implementation steps, because they are not a programming language. This restriction causes a change in the conceptual framework used to

consider the system; this rupture is error prone, entailing additional works and making the project's traceabibity difficult.

The original aim of CoOperative Objects (**COO**s) is to provide a PN-based formalism bridging the gap between the early steps of software development processes and the final steps (detailed design, programming, test). Such a formalism should provide all the people involved in a project with a single conceptual framework supporting the tasks contributing to the development of the software. The main requirements for such a formalism are as follows.

- PNs fail to account for the data processing dimension of systems. Indeed, most of the operations which cause a state change of a system also process some data, and thus it is necessary to consider tokens of a PN as data structures. Consequently, PNs have to be associated with a language permitting to define data structures and to describe how they are processed. Languages based on the Object-Oriented (**OO**) approach seem to be appropriate since passive objects and tokens have many properties in common.
- Modularity is an essential principle of System Engineering, and PNs fail to structure the model of a system as a collection of interacting components. As a consequence, it is necessary to introduce concepts which on the one hand provide each PN with an interface and on the other hand define how nets interact through their respective interfaces. Once again, the OO approach offers concepts which have proved to be efficient and a PN may be viewed as an active object.
- The main advantages of PNs are their cognitive simplicity (even though it is difficult to think about concurrent systems), their wide range of use (thanks to their abstract nature), and their suitability for behavioural formal analysis. An increase in the expressive power of PNs must no be offset by a decrease in their valuable features. Namely, even if PNs are supplemented with mechanisms that are beyond the scope of the behavioural analysis techniques, it should still be possible to keep these additions apart if we want to continue applying the analysis techniques.

According to these requirements, a PN is transformed into a CoOperative Object (**O**bject for short) by the following improvements.

1. The definition of a PN comes with the definition of object classes, using a sequential OO Programming Language, and tokens are instances of these classes. To process tokens, each transition is provided with a piece of code: when a transition occurs, this code is applied to the tokens involved. In addition, an Object may be provided with a data structure accessible by all the transitions of the PN.
2. Objects communicate through an asynchronous client/server, or request/reply protocol supported by token sending: when an Object C requests a service from an Object S, (1) C sends an argument-token into the appropriate place of S, (2) S processes this token as soon as the service is available and produces a result-token. The communication ends when (3) C retrieves this token. In addition, an Object may synchronously access public elements of the data structure of other Objects.

The introduction of these two basic tricks must result in a formalism facilitating the respect of the main principles of Software Engineering: rigor and formality, separation of concern, modularity, abstraction, anticipation of change, generality and incrementality [Ghezzi...91]. This requires thoroughly combining the fundamental concepts of the PN and OO approaches.

It turns out that the COO formalism solves another problem, which could also have been a guideline leading to this formalism.

Thanks to encapsulation, the OO approach seems to be well adapted for dealing with distributed systems. However, the state of the art proves that dealing with concurrency is difficult within the OO framework [Agha...93]. Indeed, many OO languages allow for inter-object concurrency, but very few allow for intra-object concurrency. In the lack of this latter feature, an object is a passive component since its activity consists of executing its methods upon request. Moreover, communications among objects are synchronous, since an object blocks when it waits for a reply, and this causes the behaviours of the objects of a system to be tightly coupled. On the other hand, intra-object concurrency turns objects into proactive and autonomous components able to concurrently process several tasks and to communicate asynchronously. This feature significantly improves the concurrency within the whole system, and objects gain a stronger cohesion because they are relieved of useless synchronisation constraints. Another problem raised by concurrency within the OO framework is a general and formal definition of inheritance, one of the key OO concepts [Wegner 88].

The essential requirement when enhancing OO languages in this way is to base concurrency within and among objects on a powerful and formal model of concurrency (notice that Occam, which is based on Hoare's CSP paradigm [Hoare 78], meets this requirement [May 87]). Now, an object is transformed into a CoOperative Object by the following additions.

1. The definition of an (active) object class comes with the definition of a PN which determines the behaviour of any instance of this class, so that the activity of an object consists of executing this control structure net. Namely, this net defines the availability of the services offered by the object.
2. The PNs of objects communicate through an asynchronous client/server protocol supported by token sending.

Thus, the COO formalism integrates the PN and OO paradigms into a single conceptual framework. From a PN point of view, it is a High-Level Petri Net formalism [Genrich...81, Jensen 85] which can handle the data processing dimension of systems and allow to structure models according to the OO principles. From an OO point of view, the COO formalism is a formal and fully concurrent language where Objects are proactive and able to concurrently process several tasks. We believe that combining the PN and OO approaches must produce a formalism which extends each of the two approaches, in order to retain the respective benefits of both. In order to achieve this, PNs have to be introduced into objects and conversely objects have to be introduced into PNs. The COO formalism works in this way: PNs are integrated into objects to make them active, and objects are integrated into PNs to provide them with data processing capabilities. The purpose of this paper is to give a comprehensive introduction to CoOperative Objects, thus it does not provide theoretical justifications of the design decisions. We simply stress the fact that any integration of the PN and OO approaches has to reconcile tightness with looseness. In order to retain the expressive power of both approaches, a tight integration accounting for the mutual dependence between the data structure and the control structure of Objects is necessary. On the other hand, reaping the pragmatic and theoretical benefits of both approaches requires a distinct integration which does not confuse their respective mechanisms.

The second chapter of this paper surveys the expressive power of the COO formalism. The third chapter details the definition of an Object and of a COO system, and addresses the COO's model of concurrency along with the dynamic creation and deletion of Objects. The static case of the dining philosophers problem is used as an example. The fourth chapter proposes a solution for the dynamic case of the dining philosophers problem which turns out to be a quite complex one. The fifth chapter presents the inheritance relationships among COO classes and the conditions for a COO class to be a subtype of another class; thanks to this subtype relationship, the COO formalism allows for polymorphism, which means that an instance of a subtype may be safely substituted when an instance of a type is expected. The sixth chapter indicates how various semantics of the COO formalism are defined and how the analysis techniques founded on the PN theory may be applied.

The last chapter presents an environment for the development of COO systems. SYROCO (an acronym for SYstème Réparti d'Objets CoOpératifs) is mainly a COO compiler: it translates each COO class into a C++ class so that an instance of a COO class is implemented as an instance of the corresponding C++ class. Each Object is provided with an interpreter, a Token Game Player which executes the Petri net defining its behaviour; thus an Object is actually implemented as an autonomous process. Thanks to these features, SYROCO is efficient in space and time. The COO formalism may be viewed either as a tool for the specification, the design and the analysis of complex systems, or as a Concurrent Object-Oriented Programming Language. Accordingly, SYROCO is intended to be used either as a simulation tool or as a programming environment, and it provides users with a number of facilities for both purposes. Some of these facilities are pragmatic and intended to ease the development of complex COO systems. Other facilities allow a fine control of the behaviour of each Object.

2. COOs: an Overview

This chapter gives a general presentation of the structure and the behaviour of a COO system. The COO formalism views a system as a collection of active Objects, each Object being an instance of its COO class. While a COO system is running, the set of its member Objects may vary since Objects may be dynamically created and deleted. The behaviour of a COO system results from the concurrent behaviour of its Objects, each one processing its own activity. This activity involves communicating with other Objects according to a request/reply protocol.

The structure of an Object has two parts - a *Data Structure* and a *Control Structure* (Cf. Figure 1).

The Data Structure of an Object complies with the usual concept of an object. It includes a set of *attributes* and a set of functions, referred to as *operations*. The *public* elements of this Data Structure may be accessed in a *synchronous* way by other Objects, namely by the body of their operations.

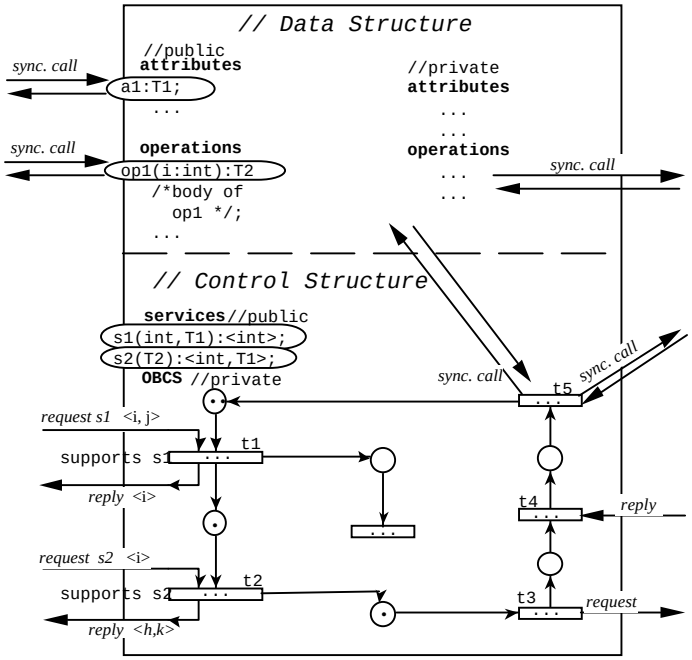


Fig. 1. The structure of a CoOperative Object

The Control Structure of an Object makes it active. It includes the declaration of a set of *services* and a High-Level Petri Net referred to as its *OBCS* (for OBject Control Structure). This net defines the Object's behaviour. Its places serve as *state variables* of the Object; thus, the value of a place is a set of data objects. The transitions of the OBCS correspond to *actions* that the Object is able to perform; thus the current state of an Object determines the enabling of its actions, and the occurrence of an action produces a change of state. In order to process the data objects staying in places, each transition may include calls for operations or more generally a piece of code which has access to the Data Structure of the Object and to the public elements of the Data Structure of other Objects (Cf. transition `t5`). As for services, they allow *asynchronous request/reply* communications among Objects. Each service is supported by transitions, and is available only when (at least) one of these transitions is enabled (Cf. transition `t1` or `t2`); if this is not the case, a request for a service is delayed until one of its associated transitions becomes available. In order to request a service from another Object, the net includes a pair of transitions: the first of these transitions issues the request, while the second one becomes enabled upon reception of the result of the request (Cf. transitions `t3` and `t4`).

Thus, the activity of an Object consists in executing its OBCS as a background task, while processing the calls for its public operations upon request. The behaviour of a COO system results from the concurrent activity of its member Objects. The main distinctive features of the COO formalism are probably the *autonomy* of Objects (from an OO view) and the *dynamism* of COO systems (from a PN view). Autonomy requires (and is achieved by) two related mechanisms. The first one is a high-level communication protocol allowing each Object to distinguish its internal activity from

its interactions with other Objects, so that its contribution to the activity of the whole system is clearly determined; the second one is the capability of each Object to have several tasks in hand at one time and thus to organise its activity according to its constraints and goals. Concerning dynamism, the possibility for COO systems to introduce new Objects or to remove member Objects without centralised control means they can cope with systems having a variable structure, and this feature significantly extends the class of systems with may be considered using PNs. Thanks to these features, the COO formalism is appropriate for the class of Open Distributed Systems [Gasser 91].

Due to lack of space, we cannot discuss to what extent the COO formalism fulfils the principles of Software Engineering mentioned above, although such a discussion is essential to validating this formalism. Therefore, we leave it to the reader, and just give a hint ! A formalism is mainly a cognitive tool allowing engineers to understand the system which they are faced by developing a model, a description, or a design of that system. For this purpose, a formalism has to provide high-level abstractions which are as close as possible to the concepts used to discuss the structure and the behaviour of systems, so that the model's architecture mirrors the organisation of the system as it is viewed by the designer.

In order to meet this requirement, the COO formalism relies upon the following meta-model: a system is embedded in an *environment* with which it interacts through an *interface*, and it may be viewed as being located in a four-dimensional space. These dimensions concern the *Entities* processed by the system, the *Operations* whose executions constitute the processing, the *Actors* which manage the entities and perform the operations, and the *Control Structure* which defines the system behaviour. Together, the current Entity instances, Operation occurrences and Actor instances of a system define the *state* of the system. These three dimensions constitute the static part of the system: as long as it is not provided with a Control Structure, a system carries out no work and its state never changes. Indeed, a change in the system's state only results from the occurrence of an *action*, that is the actual execution by an Actor of an Operation involving some Entities, and the role of the Control Structure is just to determine under which state(s) an action may occur. Once a system has been analysed according to this meta-model, it becomes easy to draw a COO model of this system through using the following correspondences: Entity/token, Operation/code associated to a transition, Actor/CoOperative Object, Control Structure/OBCS.

3. The CoOperative Objects Formalism

We shall now introduce the CoOperative Objects formalism using the static case of the dining philosophers as an example: the philosophers are steadily seated around the table. First, a centralised solution by means of a single Object of the class `PhiloTable` will be presented, allowing the structure and the semantics of an isolated Object to be introduced. Then, a decentralised solution modelling each philosopher as an Object of the class `SPhilo` will be presented, allowing the structure of a COO system and the interactions among Objects to be introduced.

3.1 A CoOperative Object in Isolation

The definition of COO classes is based on a sequential OO language, referred to as the *data language*, and SYROCO uses the language C++ for this purpose. This data language is used to define the types of tokens, attributes and parameters of COO classes, and also to define external functions and constants. These definitions are located in appropriate files and are shared by the classes of a system. In the case of the `PhiloTable` class, the C++ declarations given in Figure 2 are assumed. The data language is also used to code the operations of Objects as well as the pieces of code associated to transitions and places of the control structure net.

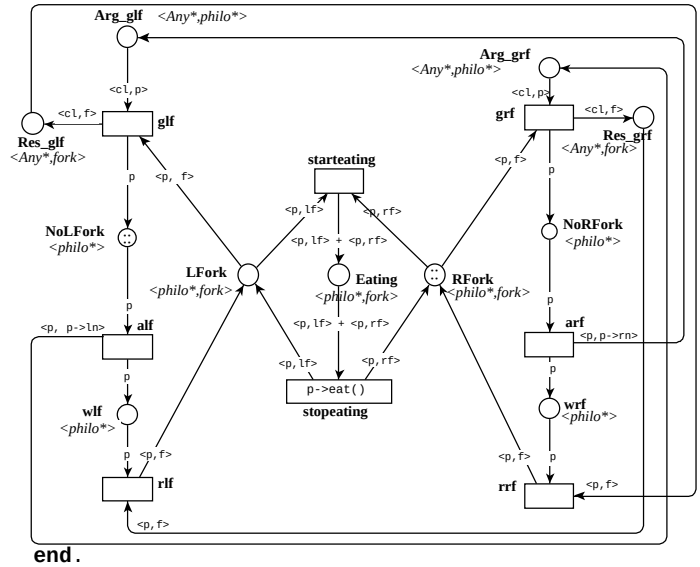
```
class Any;
class philo: Any {      //philo inherits Any
public:           //items accessed by the net
philo* rn;           //the right and left neighbours
philo* ln;
              //counts how many times the philo eat
short nbeating;
void eat() {
  nbeating = nbeating + 1;
  };
void init(philo* l, philo* r){
  ln = l; rn = r;
  nbeating = 0;
  }
};
typedef int fork;
const nbphil = 4;
```

Fig. 2. External declarations used by the `PhiloTable` COO class

The `PhiloTable` class, shown in Figure 3, is a centralised solution to the dining philosophers problem. An Object of this class considers philosophers as data entities and it controls the behaviour of them all; when a philosopher is in a given state, the place corresponding to this state contains a token referring to this philosopher.

```
Class PhiloTable specification;
operations
 Init() ///         //set the neighbourgs of each philo
thephilos[1].init (thephilos[nbphil], thephilos[2]);
   for (int i=2; i<=nbphil-1; i++)
     thephilos[i].init (thephilos[i-1], thephilos[i+1]);
   thephilos[nbphil].init(thephilos[nbphil-1], thephilos[1]);
                    //set the initial marking of the OBCS
   for (i=1; i<=nbphil; i++) {
    RFork.ADDTOKEN (RFork.MakeToken(&thephilos[i], i));
    NoLFork.ADDTOKEN (NoLFork.MakeToken(&thephilos[i]));}
  ///
end.

Class PhiloTable implementation;
attributes
 thephilos: array[nbphil] of philo;
OBCS
```




```
end.
```

Fig. 3. Definition of the PhiloTable COO class

The definition of a COO class consists of a specification part and an implementation part. The *specification* contains what must be known about the class in order to use it properly. It includes the definition of the items of its interface - attributes, synchronous operations and asynchronous services- and it may be completed with an OBCS. This specification OBCS is only intended to document the observable behaviour of class instances. As for the *implementation*, it includes the definition of private items and of the actual OBCS of the class instances.

The `PhiloTable` class has a very simple specification, since it is intended to run in isolation and to have no communication with other Objects. It only features one special operation, named `Init`, which allows to initialise the attributes and the OBCS's marking. In the general case, operations are functions accepting arguments and returning a value computed from these arguments and the Object's attributes.

Syntactically speaking, the signature of an operation follows a Pascal-like syntax, while its body (written in the data language) is enclosed between occurrences of the character string '`///`'

The implementation of the `PhiloTable` class comprises one attribute, which is an array of `philo`'s. In the general case, the type of an attribute is any type of the data language, namely a scalar type (e. g. Integer, `fork` or any enumerated domain), an object class (e. g. `philo`), or a *reference* towards an object class (e. g. `philo*`). The implementation of this class does not contain any operation.

The OBCS of an Object is a *Petri Net with Objects* (**PNO**), an extension of PNs allowing to handle tokens which are objects [Sibertin 85, 92]. The initial marking of the OBCS of the class `PhiloTable` is given by the `Init` operation which puts one reference towards each philosopher into the place `NoLFork` (for No Left Fork), and one reference toward each philosopher along with a fork into the place `RFork` (for Right Fork). This OBCS defines the following behaviour. When a philosopher has his left and right forks (places `LFork` and `RFork`), he may `starteating` and then `stopeating`. When he has his right fork and there is a request token for him in the place `Arg_grf`, the transition `grf` (for give right fork) occurs and he has no longer his right fork. When a philosopher has no right fork, the transition `arf` (for ask right fork) occurs for that philosopher resulting in a token sent to his right neighbour in the place `Arg_glf` and a token put into the place `wrf` (for wait right fork); then the `glf` transition may occur with the requested philosopher, since this latter must have his left fork; finally, the transition `rrf` (for receive right fork) occurs providing the requesting philosopher with his right fork again. The same behaviour is defined symmetrically on his left side. Thus a philosopher only needs to know the identity of his two neighbours to share the forks on his left and right sides.

This solution to the dining philosophers problem is a non-deterministic one, and it is fair (each philosopher eats infinitely often if the table is set up during an infinite length of time) if the OBCS is executed in a fair way. By means of appropriate guards, each philosopher could be compelled to give his forks before eating again.

We shall now provide technical details on the structure and the semantics of an OBCS.

The type of a *Place* (written in italic characters) is a list of types of the data language, and its value, or its *marking*, is the (multi-)set of tokens it contains. At any moment, the OBCS's state (or its marking) is defined by the distribution of tokens onto places.

According to the length of the type of the place, a *token* is either a raw-token with no specific value if the place's type is empty, a value belonging to the single data type of the place, or a list of values. Such a value is either a constant (e. g. 2 or 'Hello'), an instance of a class of the data language, or a reference to such an instance. As an example, the place `RFork` contains tokens which are made up of a reference towards a `philo` and an integer. One may wonder what the difference is between using an object class or a reference to this class in the type of a place. In the former case, the class instances are accessed 'by value', while in the latter case they are accessed 'by reference'. Thus, if an object appears among the values of a token, it makes no sense for another copy of this object to appear in another token of the same marking ([Sibertin 85] provides a structural condition to avoid this kind of *ubiquity* of objects); such a situation would go against an essential principle of the OO approach according

to which each object is unique. On the other hand, a reference towards the same object may appear in several tokens of a marking; for instance, the transition `grf` is enabled if the variable `p` is bound to an object reference which appears both in a token lying in the place `RFork` and in a token lying in the place `Arg_grf`.

If the data language supports a subtyping relation, the type of a token lying in a place may be a subtype of the place's type.

A *Transition* is connected to places by directional arcs.

Each *arc* is labelled with a list of variables having the same length as the type of the place to which the arc is connected. These variables serve as formal parameters for the transition and define the flow of token values from input places to output places. A transition *may occur* (or is *enabled)* if there exists a *binding* of its input variables with values of tokens lying in its input places. The *occurrence* (or the *firing)* of an enabled transition changes the marking of its surrounding places: tokens bound to input variables are removed from input places, and tokens are created and put into output places according to variables labelling output arcs. As is usual in High-Level Petri nets, an arc may be labelled with a formal sum of lists of variables (cf. transition `starteating`), and an expression may be found instead of an output variable (cf. transition `arf`).

The type of variables labelling an arc is defined componentwise by the type of the corresponding place. If the same variable appears in the labelling of several arcs surrounding a transition, simple rules prevent the occurrence of a 'type mismatch error' [Sibertin 92, Syroco 95]. For instance, the variable `p` of the `alf` transition occurs both on the arc from the place `NoLFork` and on the arc to the place `Arg_grf`, providing respectively the types `philo*` and `Any*`. No type problem occurs since `philo` is a sub-type of `Any` and `NoLFork` is an input place while `Arg_grf` is an output place; thus the type of `p` is `philo*`.

A transition may be guarded by a *Precondition*, a side-effect free Boolean expression involving the transition's input variables and the Object's attributes or operations (Cf. transition `leave` in Fig. 7 below; syntactically, a transition of the OBCS refers to an attribute or operation of the Data Structure using the prefix `_S->`). In this case, the transition is enabled by a binding only if this binding evaluates the Precondition to true.

A transition may also include an *Action,* which consists of a piece of code in which the transition's variables and the Object's operations or attributes may take place (Cf. transition `stopeating`). This Action is executed at each occurrence of the transition and it allows the values of tokens to be processed. If an output variable of the transition does not appear on any input arc, the Action must assign a value to this variable in order to extend the binding which enables the transition; thus, if the type of the variable is an object class, each occurrence of the transition causes the creation of a new data object. Conversely, if an input variable does not appear on any output arc while its type is an object class, each occurrence of the transition entails the loss of the data object bound to the variable.

Finally, a transition may include a set of *Emission Rules*, which are side-effect free Boolean expressions involving its variables and the Object's attributes or operations. In this case, each output arc of the transition is connected to one of the Rules, and an occurrence of the transition causes the depositing of a token into the connected output place only if the Rule evaluates to true. For instance, an occurrence of the transition `leave` in Figure 7 puts tokens into places `p1` and `p3` if the expression `ok` is true and into places `NoLFork` and `RFork` if not. This trick makes the graphical

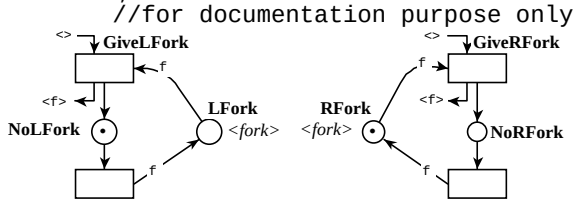
representation of the OBCS simpler since, if the Rules are contradictory, each Rule is equivalent to one transition having this Rule as a Precondition. Conceptually, providing a transition with Emission Rules makes explicit the fact that putting tokens into some places is a choice resulting from the transition occurrence.

The activity of an isolated Object consists of executing its OBCS, i. e. repeatedly firing transitions which are enabled under the current marking. When the marking of an Object concurrently enables several transitions, the Object's activity includes several threads of control, or *tasks*, which can progress concurrently. Although PNOs support semantics for the concurrent enabling and occurrence of transitions [Sibertin 92], the default semantics of an OBCS is the interleaving one: only one transition occurs at once, so that the on going tasks progress in turn. Arguments for this choice are developed in another paper [Sibertin 97a]. To summarise, from a conceptual point of view these semantics relieve the designer of difficulties entailed by the sharing of data (attributes and tokens referring to objects), and from an implementation point of view there is no real improvement of performance when the system includes several Objects.

3.2 Interactions among CoOperative Objects

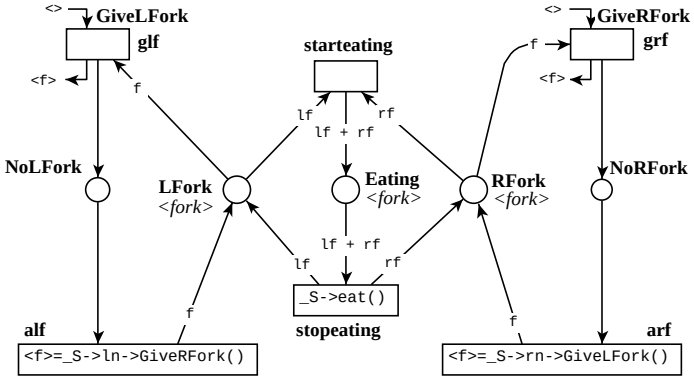
The behaviour of a COO system results from the concurrent activity of its actual Objects, and we shall now introduce cooperation among Objects through a decentralised solution of the static dining philosophers problem. Each philosopher will be viewed as an autonomous actor modelled by an instance of the COO class `SPhilo` shown in Figure 4, and a table is a set of instances of this class.
In order to be able to set communications, an Object must store references to other Objects. To this end, the types of attributes, places and parameters are allowed to be COO class references in addition to the types of the data language. But COO classes are not allowed in order to prevent the nesting of Objects. When an Object has a reference towards another Object, it has access to the public elements of that Object.

```
class SPhilo specification;
operations
 Init(n: COONAME, l: SPhilo*, r: SPhilo*, f: fork) ///
       setname(n);      //assign a unique name to the Object
       ln = l; rn = r; nbeating = 0;
       NoLFork.ADDTOKEN (NoLFork.MakeToken());
       RFork.ADDTOKEN (RFork.MakeToken(f)); ///;
services
 GiveLFork(): <fork>;
 GiveRFork(): <fork>;
OBCS                  //for documentation purpose only
```




```
end.

class SPhilo implementation;
attributes
 rn: SPhilo*;              //the right and left neighbours
 ln: SPhilo*;
 nbeating: short;    //counts how many times the SPhilo eats
operations
 eat() /// nbeating = nbeating + 1; ///;
OBCS
```




```
end.
```

Fig. 4. Definition of the `SPhilo` COO class

The public elements provided by an Object - attributes, operations and *services* - are defined in the specification of its class and they serve different purposes.

Attributes and operations are called from pieces of code of the data language and they are intended to support synchronous *data flows* between Objects. Services are called from OBCSs and are intended to support asynchronous *control flows* between Objects.

Attributes and operations appearing in a specification are defined in the same way as in an implementation. They may be called by Preconditions, Actions and Emission Rules of other Objects. They may also be called by the code of operations, but this

may cause synchronisation problems due to the synchronous semantics of operation calls. Indeed, an operation is assumed to always be available, and this property is not guaranteed if an operation calls an operation of another Object which in turn calls ... In fact, operation calls are synchronous because they are considered to be attributes whose value is computed upon request. In any case, public attributes and operations may always be removed from the interface and replaced by services. When the system under consideration is distributed and the Objects are intended to run on different computers, it is much more safe that their specifications include only services.

Services support *control flows* between Objects, that is to say interactions which have an effect upon the behaviour of the addressee and/or the applicant of the communication. A service request is asynchronous since the server may need some time to provide a result, either because its current state disables the service or because processing the request requires a lot of work. Requesting or rendering a service implies synchronisation constraints and relates to the behaviour of Objects; thus service requests and service executions are defined within OBCSs, and the specification of a class only contains the signatures of its services.

Each service provided by a COO class is implemented by a pair of places of its OBCS: an *argument-place* intended to receive tokens which are requests for the service, and a *result-place* in which the client retrieves the result of its request. (In fact, result-places may be implemented on the client side, so that the server sends the result-token to the client; but from a theoretical point of view, the contract of a server is only to make a result available for each accepted request; for instance, it is of no concern if the client disappears and leaves the result-token). Thus a service request is treated by a sequence of transition occurrences: the first transition of this sequence takes the request token from the argument-place, while the last transition puts a token down in the result-place. Graphically, argument- and result-places do not appear in the OBCS, but transitions connected to them (respectively referred to as *accept-* and *return-transitions)* bear a dangling arc labelled with the respective parameters. Of course, one transition may be both the accept- and return-transition of a service, as for the services of the `SPhilo` class in Figure 4.

In order that the services of an Object may be requested with confidence, its OBCS must be *honest* and *discreet* [Sibertin 93]. *Honesty* means that when an accept-transition of a service occurs, then a result-transition of this service is quasi-live (in other words: whatever transitions occur after the accept-transition, there is a reachable marking which enables a return-transition). If this property is lacking, some requests for this service may never receive an answer, resulting in a definitive blocking of the requesting task. *Discretion* means that a service provides a result only if it has previously been requested. If this property is lacking, some issued result-tokens would never be consumed. Honesty and Discretion are equivalent to the fact that any sequence of transitions rendering a service may be reduced to a single transition. In Figure 5, OBCS1 is not honest, OBCS2 is not discreet, while OBCS3 is neither of them. A third property that an OBCS must satisfy, reliability, will be introduced in section 5.

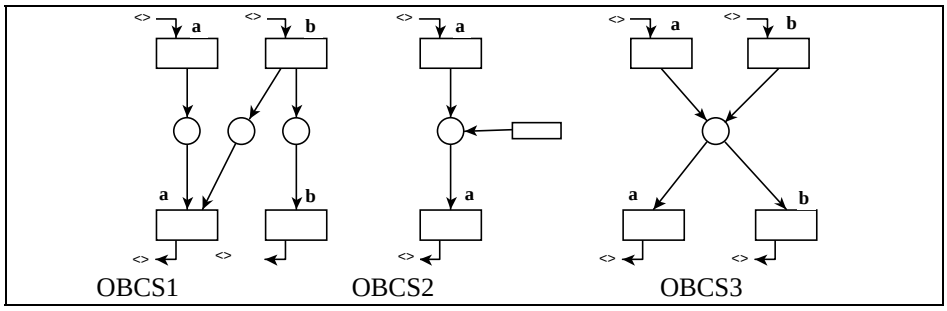


Fig. 5. OBCS1 is not honest, OBCS2 is not discreet, OBCS3 is neither honest nor discreet

A service request takes place only in the Action of a transition (Cf. transitions `alf` and `arf` in Fig. 4). When such a *request-transition* occurs, a request-token grouping together the in-parameters of the request is put into the argument-place of the server's service; when the result-token of this request is available, the transition retrieves it from the corresponding result-place and completes its occurrence. Thus, it is possible that the occurrence of a transition requesting a service lasts for some time, until the server provides the result. However, other transitions may occur in the meantime so that a client is not blocked by a service request. Indeed, the formal semantics of a request-transition splits the transition into two: one transition for sending the request-token and another for retrieving the result-token, connected by a *waiting place* which holds the request identifiers (as an illustration, compare the transition `alf` of a `SPhilo` with the transitions `alf` and `rlg` of a `PhiloTable`).

The communication amongst Objects through services implements an asynchronous request/reply protocol, which allows designers to concentrate on conceptual issues without necessarily being concerned with the details of interactions. The expressive power of this protocol extends the asynchronous message sending protocol of Actors [Agha 86] since a transition may request a service using the ''without reply'' mode (Cf. transition `t3` in Fig. 7 below). In this particular case, only a request-token is sent to the server: this latter does not produce a result-token and the request-transition is not split. This protocol also extends the synchronous request/reply and rendezvous protocols, since a request-transition may disable all the transitions of the OBCS except the one retrieving the result-token, and in this way block the Object until communication is completed.

The OBCS of an Object determines both its internal behaviour and its asynchronous communications with other Objects, that is to say:

- its spontaneous activity (transitions `starteating` and `stopeating`), as an autonomous Object,
- the service requests it issues to other Objects (transitions `alf` and `arf`), as a client, and
- the availability of its services and the way requests are processed (transitions `glf` and `grf`), as a server.

Indeed, the internal behaviour of an Object can not be dissociated from its communications with others, since synchronisation constraints introduce a mutual dependence between these two dimensions: the state of an Object determines when requests are issued, accepted and answered, and the availability of requests and

replies determines the behaviour of the Object. Nevertheless, the request and the processing of services are implemented by specific items of OBCSs, so that at the syntactic level, the 'synchronisation code' is clearly isolated [Matsuoka... 93]. When dealing with the conceptual design or the behavioural analysis of an Object, it is easy to focus either on its server side, on its client side, or on its internal behaviour.

As far as intra-Object concurrency is concerned, the model of the COO formalism is the interleaving semantics (Cf. 3.1). Concerning the inter-Object level of concurrency, the COO formalism adopts the true parallelism semantics, i. e. any number of Objects may fire a transition of their OBCS at the same time. The implementation issues caused by these semantics will be addressed in chapter 7.

3.3 Creation and Deletion of Objects

The COO formalism supports the dynamic creation and deletion of Objects. This feature is illustrated by the `DPhilo` class which models the dynamic dining philosophers problem (Cf. Fig. 7): each occurrence of transition `t7` brings about the introduction of a new `DPhilo` around the table, and a `DPhilo` disappears when firing its transition `dead`.

An Object of a system introduces a new Object into this system by creating a new instance of a COO class and calling its `Init` operation. Then, the new Object becomes active; more precisely, it starts the execution of its OBCS after the execution of its `Init` operation. Since introducing a new Object into a system concerns the behaviour of the whole system, it must take place in the Action of a transition.

The deletion of an Object is more problematic. An Object is considered as being dead, and can thus be deleted, only when no other Object has a reference to it (so it can no longer receive an operation or service call) and in addition it has reached a dead marking (so it has nothing to do). A `DPhilo` satisfies this requirement, since firing the transition `dead` produces a dead marking. An implementation of COOs could include a Garbage Collector based on this principle. However, it is better if the deletion of an Object explicitly occurs in the Action of a transition, since it greatly concerns the behaviour of the whole system.

In any case, the deletion of an Object has to comply with the constraints of the asynchronous request/reply protocol:

1. when an Object, as a server, has received a request-token which enables an accept-transition, it cannot be deleted before it provides a result for this request. On the other hand, if the request-token does not enable any accept-transition, it is possible to consider that the Object has been misused by the issuer of the request.
2. when an Object, as a client, has issued a request for a service, it cannot be deleted before it retrieved the result of this request.

Anomalies resulting from the breaking of these rules may be considered both from the Petri Net and programming language points of view. From the PN point of view, in the first case a token will be blocked in the waiting place of the client, and in the second case a token will be blocked in the result-place of the server. Considering the COO formalism as a programming language, a task of the client will be blocked for ever in the first case, and in the second case an ''invalid reference'' run-time error will occur when the server sends the result. SYROCO does not include a Garbage Collector, but the function `coodelete` returns an error status and does not delete the Object if the two rules mentioned above are not satisfied.

4. The Dynamic Philosophers Case Study

A decentralised solution for the dynamic philosophers problem is proposed in this chapter, in order to illustrate the expressive power of the COO formalism with regard to the dynamicity of Objects. In this case, philosophers may join or leave the table. The corresponding COO system includes one instance of the class `Heap` in charge of keeping the forks used by the philosophers, and a dynamic set of instances of the class `DPhilo`; an instance of this set can create new instances of the class `DPhilo` (and so introduce new guests) and can also delete itself (and so leave the table).

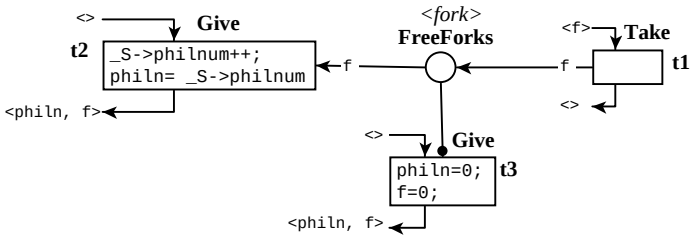
To ensure that a table of dynamic philosophers remains bounded, the number of forks is limited, and they are kept by an Object of class `Heap` shown in Figure 6. The service `Give` is intended to supply a fork from the `Heap`, while the service `Take` stores a fork in the `Heap`. A new philosopher may be introduced at the table only if a request for the service `Give` has returned a fork, and a departing philosopher gives his fork back by requesting for the service `Take`. Transition `t3` returns nothing if no fork is available. Thanks to this transition, the service `Give` is always available either through transition `t2` (when there are forks in the place `FreeForks`) or through transition `t3` (when there are none). Thus, requests for service `Give` are never delayed; this prevents the system from blocking when no fork is free and all the philosophers around the table simultaneously request a fork.

As far as eating and the exchange of forks are concerned, a dynamic philosopher behaves as a static one, so that the class `DPhilo` shown in Figure 7 inherits the attributes, the services and the OBCS of the class `SPhilo`. With regard to joining and leaving the table, the logic of the dynamic philosophers is much more complex. In fact, the instances of class `DPhilo` have to build a ring of Objects which is:

- consistent: each Object knows its current left and right neighbours and communicates only with them,
- dynamic: Objects may leave or join the ring,
- decentralised: there is no global supervisor who knows the setting of the table.

```
class Heap specification;
operations
 Init(nbfork: int) ///
   setname ('The Heap');
   philnum = 0;
   for (fork i=1; i<=nbfork; i++)
          FreeForks.ADDTOKEN (FreeForks.MakeToken(i));
    ///;
services
 Take(f: fork);
 Give(): <int, fork>;
end.

class Heap implementation;
attributes
 philnum: int;   //to give a number to each Philosopher
OBCS
```




```
end.
```

Fig. 6. Definition of the COO class `Heap`

According to the statement of the dynamic dining philosophers problem, the `DPhilo` class must be designed in such a way that the two following requirements are ensured at any moment:

R1: one and only one fork is shared by two adjoining Philosophers;

R2: on both the left and right sides of a philosopher, every request sent to the neighbour is received by the real neighbour, and every reply is received by the real neighbour; for instance, the following must never happen: a request is sent to a philosopher who has left, a philosopher leaves with a pending request which will be never answered, a philosopher leaves without waiting for the result of a request, or a new philosopher is introduced between the sender and the addressee of a request.

Requirement R1 is easy to ensure, for instance by means of the following rule:

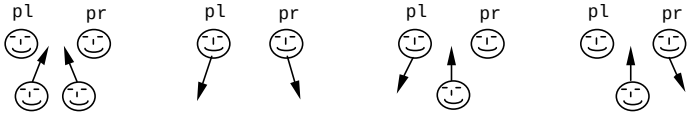
(**1**) a philosopher joins or leaves the table

- with a right fork (while his right neighbour has no left fork), and
- without a left fork (while his left neighbour has a right fork).

Requirement R2 is more difficult to ensure in the absence of centralised control. It implies that there is no concurrent moves at two adjacent places around the table. For instance, let us consider two adjoining philosophers *pl* and *pr*, and *p1* and *p2* be concurrently introduced between them; *p1* and *p2* do not know each other, so that they will both have a reference towards *pl* as their left neighbour and towards *pr* as

their right neighbour, and this is clearly wrong. Thus, if *pl* is at the left side of *pr*, the following cases must be avoided:

c1: two philosophers are simultaneously introduced between *pl* and *pr*,
c2: *pl* and *pr* concurrently leave the table,
c3: *pl* leaves the table while a philosopher sits down on his right, and
c4: *pr* leaves the table while a philosopher sits down on his left.

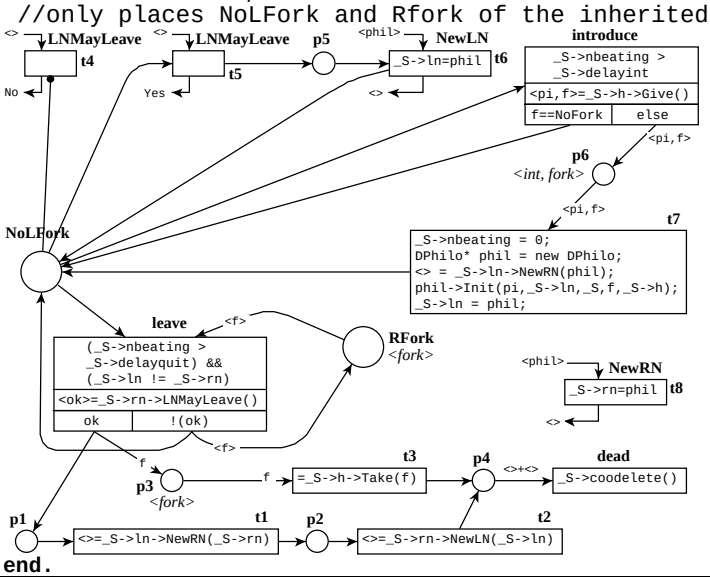


Several policies ensure that such cases never occur; among them, we choose the following one:
(**2**) a Philosopher joins the table only if he is introduced by an already installed colleague, and he sits down on his lefthand side (so c1 is avoided);
(**3**) a Philosopher does not concurrently introduce a new guest and leave (c4 avoided);
(4) when a philosopher intends to leave, he asks his right neighbour for the permission to leave; this latter refuses if he himself is leaving or introducing, and when he accepts, he is prevented from leaving and introducing until he knows his new left neighbour (c2 and c3 avoided).

The OBCS of the class `DPhilo` implements this policy (among the elements inherited from the OBCS of the class `SPhilo`, only places `NoLFork` and `RFork` appear in Figure 7).

When joining, rule (1) is ensured by the initial marking produced by the operation `Init` and the fact that a philosopher tries to introduce a new guest only when he has no left fork; when leaving, (1) is ensured by the fact that places `NoLFork` and `RFork` are input places of the transition `leave`.

```
class DPhilo specification;
inherits SPhilo;
operations
 Init(id:int, l:DPhilo*, r:DPhilo*, f:fork, hp:Heap*) ///
       setname (“Philosopher”,id);
       ln = l; rn = r; h = hp;
       delayquit= rand()%4; delayint= rand()%6; nbeating= 0;
       NoLFork.ADDTOKEN (NoLFork.MakeToken());
       RFork.ADDTOKEN (RFork.MakeToken(f)); ///;
services
 LNMayLeave(): <Bool>;
 NewLN(phil: Dphilo*); NewRN(phil: DPhilo*);
end.
class DPhilo implementation;
attributes
 rn, ln: DPhilo*;        //redefined as a Dynamic Philosopher
 h: Heap*;
 delayquit, delayint: short;  //to make DPhilos a bit steady
OBCS
inherits SPhilo;
 //only places NoLFork and Rfork of the inherited OBCS are shown
```




```
end.
```

Fig. 7. Definition of the COO class `Dphilo`

Rule (2) is ensured by the Action of the transition `t7`.

The mutual exclusion of leaving and introducing (rule (3)) is enforced by place `NoLFork`, since a `DPhilo` may introduce a new guest or leave the table only when his place `NoLFork` contains a token.

As for rule (4), it is ensured by the fact that the service `LNMayLeave` is also in mutual exclusion with introducing and leaving by means of place `NoLFork`. This service is supported by transitions `t4` and `t5`; thus it is permanently available and this prevents the system from blocking when all philosophers simultaneously intend to leave.

The Precondition of the transition `leave` guarantees that at least two philosophers remain around the table.

Only the general principles of this solution have been given here, leaving out the justification of some details: for instance, `NewLN` and `NewRN` must be services and not public operations, transition `t1` must occur before `t2`, in the Action of transition `t7` the lefthand neighbour of the introducing philosopher needs to know his new righthand neighbour before the latter starts his activity, and transition `t8` must have a higher priority than transition `leave`. One should note that, since this net is bounded, inhibitor arcs and priority of transitions are used only to simplify the graphic representation. When executing this system with SYROCO, runs of ten million transition occurrences with fourteen forks in the `heap` create about 22,600 philosophers and the remaining ones are among the last 50 to be introduced.

5. Inheritance and Sub-typing

Inheritance is one of the main concepts of the OO approach as it is both a cognitive tool which eases the design of complex systems and a technical support for software reuse and change [Meyer 88]. However, it has been pointed out that inheritance within concurrent OO languages entails many difficult problems or anomalies [Matsuoka...93]. These difficulties are due to the fact that, for a long time, inheritance has been confused with the concept of type [America 90]. *Inheritance* refers to the reuse of the components of a class by another one, so that the derived class includes elements inherited from its parent class together with its own elements. As for the concept of *type*, it is not specific to the OO approach and relies on the substitution principle: *s* is a subtype of *t* if an instance of type *s* may be substituted when an instance of type *t* is expected [Wegner 88]. Inheritance is a matter of structure sharing and it mainly relates to implementation issues, while typing is a matter of polymorphism and it mainly relates to the specification (the observable behaviour) of objects. These two viewpoints are quite close when sequential OO languages are considered, but there is no denying that they are far from each other when PNs are taken under consideration.

The COO formalism supports three kinds of inheritance.

Specification inheritance is aimed at supporting the subtype relation. In this case, the derived class includes the declaration of the public attributes of the inherited classes, and the signature of their public operations and services. In addition, it is

possible to redefine (or *override)* the type of the arguments of operations and services according to the contravariant rule, and the type of their result according to the covariant rule. The *contravariant* rule specifies that the type of a parameter may be replaced by a supertype, and the *covariant* rule says that the type of a parameter may be replaced by a subtype. Thus, a class derived by specification inheritance offers an interface which is compatible with those of the base classes, but it does not share their code.

Implementation inheritance strengthens specification inheritance and enables the derived class to share the code of operations. In this case, the derived class includes the declaration of the attributes and services of the base classes, as well as the definition of their public and private operations; but the OBCS is not inherited and the derived class has its own one.

In the *OBCS inheritance* case, the derived class fully inherits another class; it inherits its specification and its implementation, including the OBCS. Multiple inheritance is not allowed, in order to prevent problems arising from the merging of OBCSs.

Subtyping includes two aspects: when a call for an operation or a service is addressed to an instance of the subtype instead of an instance of the supertype,

1. the type of the formal parameters of the subtype has to match the type of the actual parameters of the call, and
2. the requested service has to be available at the subtype instance if it would have been available at the supertype instance.

The first aspect warrants the safety of data types, while the second aspect warrants the safety of the behaviour. For instance, the class `DPhilo` is not a subtype of the class `Sphilo`, since a `SPhilo` provides its `GiveLFork` and `GiveRFork` services for ever, while a `DPhilo` stops as soon as it leaves. Conversely, class `SPhilo` is not a subtype of class `DPhilo` since this latter offers additional services.

Specification inheritance guarantees that the interface of the derived class offers the same possibilities of interaction as the interface of the base class, and a class B may be a subtype of a class A only if B inherits the specification of A. The authorised redefinitions of signatures preserve this compatibility, and it is commonly agreed that they maintain the type-safety of data exchanges [Liskov...93].

Figure 8 shows three classes which are in specification inheritance relationship but which feature different behaviours: a client of an instance of class A will successfully request the sequence of services "c b c b ...", while it will block if it attempts to do the same with an instance of class B, and it will succeed if it does the same with an instance of class C. Class C is a subtype of class A, while class B is not because it is unable to simulate the behaviour of class A.

In [Hameurlain...99], conditions upon the OBCS of two COO classes are given ensuring that one of them is a subtype of the other. The first condition is that any sequence of service requests which is accepted by the supertype is also accepted by the subtype. The second condition, referred to as *reliability,* concerns only the OBCS of the subtype; it requires that, whatever the marking reached by the Object, the set of services which are available under this marking only depends on the sequence of service requests which have been previously accepted. In other words, if two markings are reached while accepting the same sequence of services then these markings enable the same service requests. Figure 9 shows typical examples of

OBCSs which are not reliable, while all the COO classes presented within this paper have a reliable OBCS. If the OBCS of a class does not satisfy this property, this class is a subtype of no COO class. In fact, any COO class should have a reliable OBCS; if not, the class has

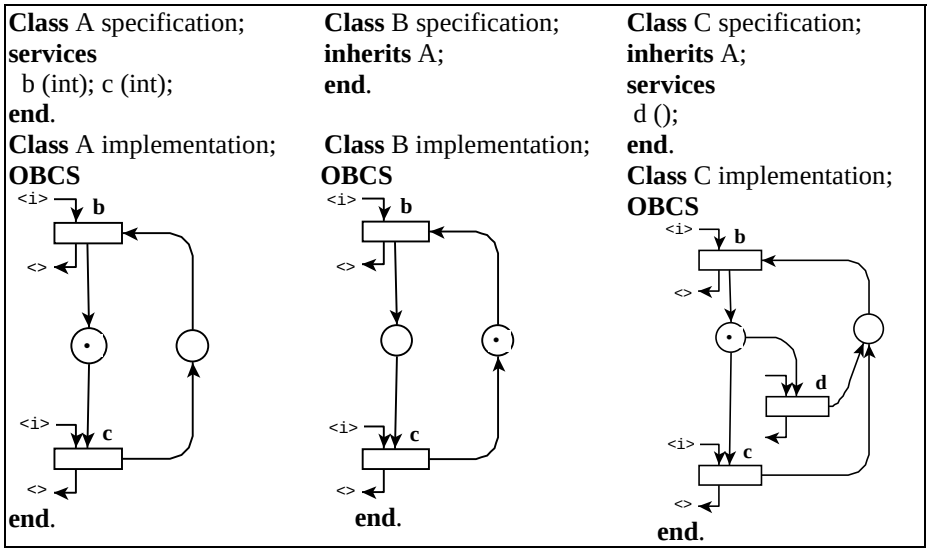


Fig. 8. Class C is a subtype of class A, while class B is not

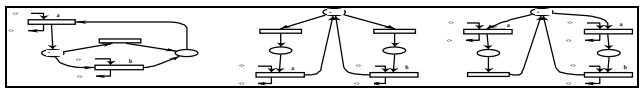


Fig. 9. Typical examples of unreliable OBCSs

an unsafe behaviour, since a client has no means to know whether its next request will be accepted or not. It is worth noting that it can be decided whether a COO class is a subtype of another one [Hameurlain...99].

6. Formal Semantics of the COO Formalism

As is to be expected, COOs enjoy a semantics which complies with the PN theory.

A basic feature of the COO formalism is that it makes a data language intervene in the definition of COO classes. Thus, any definition of a formal semantics of the COO formalism requires the data language to be provided with a formal semantics, and the COO's semantics results from the integration of the latter with the PN theory. However, we also need a pure PN semantics which would enable one to apply the PN analysis techniques to a COO system. Such a semantics would have to ignore the data processing part of Objects, and to account only for their behavioural part. The COO formalism enjoys such a semantics, which abstracts from the distinctive features of the data language and does not deal with the value of the data processed and sent by

Objects. The possibility to define such a semantics stems from the fact that COOs integrate the PN and OO approaches while not confusing their respective mechanisms.

Modularity is another basic feature of the COO formalism, which is so provided with a two-levels semantics: the semantics of an isolated Object which mainly concerns the local processing of tokens, and the semantics of a COO system which deals with the communication among Objects.

The semantics of an isolated Object formalises how the values of tokens and attributes are taken into account by the Preconditions (the enabling rule) and processed by the Actions (the occurrence rule) of transitions. This may be fully achieved only if the data language has a formal semantics. For instance, [Sibertin 92] gives a formal semantics for isolated Objects, using a formalism based upon Abstract Data Types [Ehrig...85] as the data language.

Whatever the data language, it is possible to define a pure PN semantics which accounts for the flow of tokens across the places of the OBCS but ignores their structure, their value and how they are processed by the transition occurrences. For this purpose, a COO class is modified in such a way that all the types of places are references towards classes of data objects. Thus tokens become (lists of) references to objects and include neither scalar values nor objects. These new object classes remain abstract; thus Preconditions and Actions become useless and disappear, as well as attributes and operations, since tokens are pure identifiers referring to no value. After some additional transformations accounting for the dynamic creation and deletion of Objects, a COO class may be viewed as a Well Formed Coloured Petri Net [Chiola...90], the set of identities of the instances of each object class being considered as a Colour domain.

One may wonder whether applying these modifications to a COO system changes its behaviour; in other words, to what extent a semantics of COOs, which is partial because it is based only upon the PN theory, is an accurate semantics, and to what extent the results obtained by the PN analysis techniques of a COO system really describe the behavioural properties of this system? The answer depends on the use of Preconditions. If they are used jointly with the net structure of the OBCSs to define the Objects' behaviours -as for example a Precondition which evaluates to `false` whatever the value of tokens- then the PN semantics is not accurate. On the other hand, this semantics is accurate if Preconditions are used only as they are intended for solving conflicts among transitions or tokens; in this case, for any run of an Object stripped of its data part, there exists an initial value of this Object yielding this run [Sibertin 85] (The converse clearly holds in any case). Thus, a designer may trust the results obtained by the PN analysis techniques as far as he/she respects the ‘separation of concern’ principle.

As for the cooperation among the Objects of a system, [Sibertin 94] gives formal semantics which ignore the types of tokens. In fact, this paper provides two semantics for the cooperation. The first one is straightforward and defines the change in a COO system produced by a set of Objects which concurrently fire one transition. The second semantics may be viewed as a global, or centralised one; it is defined by means of an algorithm translating a COO system into a single Object which is isolated (it provides or requests no service) and equivalent (more precisely: bisimilar) to the whole system. As an example, this algorithm translates a system of four `SPhilo`

Objects (cf. Figure 4) into an Object which is quite close to an instance of the `PhiloTable` class given in Figure 3 (the OBCS of the `PhiloTable` class accounts for the sending of tokens caused by service requests, but it does not include the elements for the dynamic creation and deletion of Objects, nor for the inheritance relation among COO classes, nor for the identification of service requests which is needed to distinguish requests concurrently issued or received for the same service).

Associating one of the semantics of communication among Objects with one semantics of isolated Objects provides the COO formalism with a complete formal semantics. The Coloured PN-based semantics are of a special interest, since they allow behavioural analysis techniques to be applied. The first way to analyse a COO system is to globally analyse the isolated Object to which the whole system is equivalent. The second way is to analyse each COO class in isolation while ignoring the specific treatment of accept-, return- and request-transitions. Then, some compositional results [Sibertin 93, Hameurlain...99] allow to incrementally deduce the behaviour of the whole system from the behaviour of its component COO classes.

7. SYROCO

SYROCO is an environment for designing COO classes and executing COO systems. It is intended to be used either as a simulation tool or as a programming environment [Syroco 96, Sibertin 97b].

A COO class is edited either using a tailored version of *MACAO*, the generic Petri net graphic editor developed at the MASI [Mounier 94], or as a text file compliant with a very simple syntax. In the former case, the MACAO file is translated into a text file before applying the following main utilities:

- *newproj*, to create the working environment (required directories and files) for a new system,
- *gencode*, to generate the C++ code associated with a COO class,
- *gentest*, to generate a main program for an instance of a COO class,
- *genmake*, to generate makefiles.

SYROCO is based on the language C++ in two ways. On the one hand, C++ is the data language used to write the code of the files containing the external declarations (as shown in Figure 2), and also to write the body of Object operations and the pieces of code embedded in the transitions and places of OBCSs. On the other hand, SYROCO generates C++ code for each COO class and implements any Object as an instance of a C++ class. The choice of C++ is contingent, and COOs can be implemented using another OO Programming Language. However, the crucial point is to use the same programming language both as the data language and as the implementation language. If two programming languages are used, the integration of the data processing and behavioural dimensions of Objects is difficult and results in poor performances, and in addition the designer-defined code embedded in an Object can access neither the kernel of SYROCO nor the Object's implementation.

Although SYROCO is mainly a COO compiler, the OBCS of each Object is not flattened into a static control structure. It is interpreted by a generic “token game player” which repeatedly looks for transitions which are enabled under the current

marking and fires one of them. This feature allows the non deterministic nature of Petri nets to be retained and provides each Object with a powerful symbolic debugger. It also allows dynamic changes of the value of some parameters of the interpreter. In this way, each Object may control how its OBCS is executed. In addition, interpreting OBCSs avoids burdening each COO++ class with a large piece of code.

SYROCO provides users with a number of facilities both for the simulation and the final implementation of complex systems. Some of these facilities are pragmatic and intended to ease the development of COO systems, while others extend the expressive power of the formalism and are intended to allow a fine control of the behaviour of each Object. They will not be addressed here, but we shall discuss the main design decision of an implementation of the COO formalism. Details about the structure and the functionalities of SYROCO may be found in [Sibertin…95a, 97b] and [Syroco 96].

7.1 Implementation of an Object

Each COO class gives rise to the generation of a C++ class, referred to as its COO++ class, in such a way that each instance of a COO class is implemented as an instance of the corresponding COO++ class. First, the compiler provides a COO class with two operations for each service, in charge of sending respectively request- and result-tokens. The compiler also transforms the OBCS of a COO class in order to implement the formal semantics of service requests (namely, argument- and result-places are added, request-transitions are split, and the sending of tokens is added to the Action of the appropriate transitions, cf. section III.2). After these modifications, the OBCS of each Object fully implements the PN semantics of the communications protocol through services.

Then, a COO class is compiled into a static data structure of the implementation language, and this is one essential reason for the efficiency of SYROCO. Only the tokens, which are implemented as instances of generated C++ classes, are stored in dynamic linked data structures. The structure of a COO++ class is very similar to the one of its COO class. A COO++ class has one member attribute for each attribute of the COO class and one member function for each operation, and also one member attribute for each place and transition of the OBCS. The class of a place attribute inherits functions for the management of tokens and it also includes specifically generated functions (the body of which is provided by the designer) to order the tokens of the marking or to be triggered upon the arrival or the departing of tokens. Similarly, the class of a transition attribute inherits general purpose functions, and it includes specifically generated functions to test its Precondition and to execute its Action. These classes of place and transition attributes are also equipped with attributes which determine the policy of the ordering of tokens into places, the priority of transitions, the delays associated with arcs, or even the hiding of tokens and transitions; an Object may change the value of these attributes while it is running and thus gains some reflexivity.

The implementation of the inheritance and subtyping relationships among COO classes heavily depends on the possibilities of the implementation language. Indeed, any reasonable means to implement the polymorphism among Objects has to be based upon mechanisms of the implementation language. Thus, SYROCO relies on the C++ inheritance mechanisms for supporting the three inheritance relationships among

COO classes (Cf. chapter V). To achieve this, a COO class gives rise to the generation of three C++ classes: one for its specification, a derived class for the attributes and operations of its implementation, and a third derived class, the COO++ class, accounting for its OBCS. The specification, implementation and OBCS inheritance relationships among COO classes are translated into inheritance relationships among the corresponding C++ classes. When implementing the COO formalism, inheritance is the only aspect which depends on the implementation language, and SYROCO suffers from the limitations of C++ in this regard.

7.2 Execution of an Object

Each Object has its own OBCS interpreter; more precisely, it inherits a generic PNO interpreter which locally executes its OBCS. Thus, each Object is actually implemented as an autonomous process that encapsulates its behaviour. As a consequence, the behaviour of a COO system features the same modularity as its structure, and there is no difficulty in taking advantage of the resources of a multi-processor computer or in distributing the Objects of a system over a network of computers [Sibertin 97a]. Of course, the concurrency among the Objects of a system requires some synchronisation between the interpreters of these Objects, but the resulting overhead is negligible. These Objects are weakly coupled (in the same way as in Actor languages [Agha 86]), since conflicts only occur on accesses to argument- and result-places for sending or receiving tokens. In any case, this solution is much more efficient than a single distributed Petri net interpreter (e.g. [Bütler…89] among others) which, being unaware of the dynamics of the Objects, has to check in all cases if a synchronisation is needed.

The default strategy of the OBCS interpreter is to fire only one transition at once, according to the *interleaving semantics*. Thus, an Object may have several on going tasks (according to the number of transitions enabled under the current marking), but each progresses in turn. The main reason for this choice is a conceptual one. Due to these semantics, the action of each transition is a critical section, and the occurrence of a transition is atomic with regard to other transitions. In this way, the designer is relieved of ensuring the mutual exclusion of transitions, even if their Actions refer to the same attribute(s). As a consequence, an Object needs to synchronise with other Objects, but it does not need to synchronise with itself since it never concurrently accesses its own data structure. From a performance point of view, the execution of one Object requests the computing environment to spawn only one process.

The principle retained for the algorithm of the interpreter is the *triggering place* mechanism [Colom...86]: to each transition is associated one of its input places, and the enabling of a transition is tested only if the marking of its triggering place is not empty. (The efficiency of this principle results from the fact that most transitions of a PN have one input place which controls their occurrence, while the other input places correspond to a synchronisation of resources. When a transition belongs to the path of the support of a place invariant, the input place of the transition which belongs to this support is a good candidate). This algorithm raises the problem of fairness: it selects the first enabled transition found and this transition occurs with the first tokens found, instead of randomly choosing a <transition, binding> couple among the enabled ones. Fairness is gained by the random nature of the search over the sets of transitions and tokens.

7.3 Concurrency among Objects

As far as concurrency among the Objects of a system is concerned, the default strategy is the *true parallelism semantics*; in other words, several Objects may be active at the same time and fire a transition of their OBCSs. This strategy causes no synchronisation overhead, thanks to the low coupling of OBCSs by token sending; if the interpreter of an Object finds an enabled transition, it may fire it without considering the choices made by the interpreters of other Objects. In conjunction with the interleaving semantics for the intra-Object concurrency, this choice makes use of the resources of the computing environment in a straightforward manner: the execution of a COO system needs as many processes as the current number of Objects [Sibertin 97a].

However, dealing with true parallelism entails implementation issues. One solution is to develop a specific runtime system which provides the required functionalities. The other solution is to rely upon the underlying operating system, using its capabilities as much as possible, as does SYROCO. As a consequence, SYROCO has to account for the actual services offered by operating systems, and thus it generates COO++ classes for sequential computing environments, for environments supporting *threads* (or lightweight processes), and also for COOL (the Chorus Object-Oriented Layer [Chorus 94]), a distributed computing environment compliant with *CORBA*.

The sequential version: The sequential version of SYROCO implements the interleaving semantics among Objects. Thus, the concurrency among Objects is only virtual. To this end, SYROCO includes a scheduler which randomly selects one Object of the system, and then activates this Object by calling its interpreter for a given number of transition occurrences. In this version, an interpreter returns as soon as no transition is enabled, since only the activation of another Object can enable a transition.

The threaded version: SYROCO implements the true parallelism semantics by delegating the actuation of Objects to the underlying operating system, according to the computing resources. In the threaded version, all Objects run in the same system process, but each one has its own thread of control. More precisely, making an Object active consists of spawning a new thread and calling the Object interpreter inside this thread, referred to as its *main thread*. As a consequence, each Object is accessed by several threads of control:

(1) its main thread,
(2) the threads of client Objects calling public operations or reading the value of public attributes,
(3) the threads of client Objects sending tokens into accept-places in order to request services,
(4) the threads of server Objects sending tokens into result-places as replies for previous service requests.

Each Object includes a mutual exclusion lock for ensuring that threads (1), (3) and (4) do not concurrently access the marking of places. As for the Object's attributes, they are accessed by threads (1) and (2) and SYROCO sets a specific lock during the execution of the Actions of transitions; thus, it is left to the designer to protect them against concurrent accesses by including appropriate get and release statements in the code of public operations, according to the logic of the system.

Contrary to the sequential version, an interpreter does not return when no transition is enabled, instead it blocks until it receives a token from a thread (3) or (4).

The CORBA version*:* This version is based on the same principles as the threaded version, and in addition it enables the Objects of a system to run on different nodes of a network. Due to this fact, it is advisable that Objects do not communicate by synchronous communications (i. e. public attributes and operations). This version relies on COOL for the remote function calls.

From a software development point of view, every one of these three versions of SYROCO is useful for finalising a COO system. The sequential version allows the designer to test and validate the behaviour of each Object as well as the cooperation among Objects; but issues related to concurrency among Objects are excluded. In the threaded version, the execution of an Action may be interrupted by operations and vice versa, and tokens may arrive at any moment. Thus, this version allows the designer to focus upon the concurrency among Objects. The issues related to the distribution of Objects are accounted for only by the CORBA version.

7.4 Performance Issues

COO++ classes include a lot of *compilation conditions* which may be selected by the user according to his/her aims. The choice among the three versions above as well as the actual use of the additional features of SYROCO (the delivery of traces and statistics, local clocks, keeping the names of places and transitions, ...) depends on these conditions. Thus, either a COO++ class is equipped with many facilities and features, or it is an optimised implementation of a COO class.

With regard to size issues, the size of the code shared by the COO++ classes of a system is around 60 K, whereas a class own code is mainly the embedded code provided by the designer. The memory required to allocate a new instance is a few Ks; for instance, the memory size required to allocate an instance of our `DPhilo` example (including 11 places and 17 transitions) varies from 2,5 to 3,6 K according to the number of compilation conditions. Thus, the PN-component of Objects is sparing of memory.

With regard to performance issues, the OBCS interpreter is quite efficient, and the overhead resulting from the concurrency is negligible with regard to the execution of Actions (in as much as they need some amount of computation). The occurrence of one million transitions of the `DPhilo` example takes about 4mn 30 on a Sun SPARCclassic station and 1mn on a Pentium 120 Windows NT PC with Visual C++. This speed does not depend on the size of the net, but it is likely to grow with the number of tokens of the marking. Indeed, the number of bindings of the input variables of a transition with tokens is equal to the product of the size of the markings of the transition's input places; so, the interpreter may have to build and test many bindings before finding out one which enables the transition.

Conclusion

The COO formalism belongs to the family of High-Level Petri Nets which attempt to overcome the inadequacy of PNs with regard to modularity and the data processing

dimension of systems. This formalism draws its inspiration from the OO approach, and it introduces all the concepts of this approach into PNs while remaining within this theoretical framework. As a result, it widens the field of use of PNs in several directions:

- The modelling and analysis of systems where the data structure plays a crucial role, such as Information Systems, Workflow or Business Procedures;
- The modelling and analysis of *open* distributed systems which include a varying number of processes communicating in an asynchronous manner;
- The use of a single PN-based conceptual framework throughout the software development process, from the system analysis and specification steps to the implementation.

From an OO view, the COO formalism is a Concurrent OO Language which supports intra-object concurrency and provides objects with a large degree of autonomy. This formalism is based on a formal model of concurrency, PNs, and it makes the techniques of this theory applicable to the analysis of the behaviour of concurrent systems. As a result, it widens the field of use of the OO approach in several directions:

- Coping with critical concurrent systems, where the formal validation of the system's behaviour is essential;
- Coping with Multi-Agent Systems or Distributed Artificial Intelligence applications, which requires turning objects into autonomous and capable agents [Gasser 91];
- To serve as a reference model for Concurrent OO Languages.

As for SYROCO, it tends to prove that formalisms integrating Petri nets and the O-O approach may be implemented in a rigorous and efficient way, provided that the principle of ''separation of concern'' is obeyed.

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References

[Agha 86] G. AGHA
Actors: A Model of Concurrent Computation in Distributed Systems. MIT Press, Cambridge, 1986.

[Agha...93] G. AGHA, P. WEGNER, A. YONEZAWA
Research directions in Concurrent Object Oriented Programming, MIT Press, 1993.

America 90] P. AMERICA
Designing an Object-Oriented Programming Language with Behavioural Subtyping. In Foundations of Object-Oriented Languages, J.W. de Bakker, W.P. de Roever, G. Rozenberg Eds., LNCS 489, Springer-Verlag, 1990.

[Bütler…89] B. BÜTLER, R. ESSER, R. MATTMANN
A Distributed Simulator of High Order Petri Nets. In Proceedings of the 10th Int. Conference on Application and Theory of Petri Nets, Bonn (G), June 1989.

[Chiola...90] G. CHIOLA, C. DUTHEILLET,G. FRANCESCHINIS, S. HADDAD
On Well-Formed Coloured Nets and their Symbolic Reachability Graph. In Proceedings of

the 11th International Conference on Application and Theory of Petri Nets, Paris (F), June 1990.

[Chorus 94] CHORUS SYSTEM.
COOL V2 Programmer's Guide. Paris, Feb. 1994.

[Colom… 86] J.M. COLOM, M. SILVA, J.L. VILLARROEL
On software implementation of Petri nets and colored Petri nets using high-level concurrent languages. In Proceedings of the 7th European Workshop on Application and Theory of Petri nets, Oxford (GB), July 1986.

[Ehrig...85] H. EHRIG, B. MAHR
Fundamentals of Algebraic Specifications. Springer-Verlag, 1985.

[Gasser 91] L. GASSER
Social Conception of knowledge and action: DAI foundations and open systems semantics. Artificial Intelligence 47, Elsevier, 1991.

[Ghezzi...91] C. GHEZZI, M. JAZAYERI, D. MANDRIOLI
Fundamentals of Software Engineering. Prentice-Hall International Editions, 1991.

[Genrich...81] H. GENRICH, K. LAUTENBACH
System modelling with High Level Petri Nets. Theoretical Computer Science 13, North Holland, 1981.

[Hameurlain...99] N. HAMEURLAIN, C. SIBERTIN-BLANC
Behavioural Types in CoOperative Objetcs. In Proceedings of the 2th Int. Workshop on Semantics of Objects as Processes, SOAP '98, within the 13th European Conf. on Object-Oriented Programming, ECOOP'99, June 1999, Lisboa, Portugal.

[Hoare 78] C.A.R. HOARE
Communicating Sequential Processes. Communication of the ACM, 21(8), 1978.

[ISO 97] Comittee Draft ISO/IEC 15909
High-level Petri Nets - Concepts, Definition and Graphical Notations. ISO SC7, October 1997.

[Jensen 85] K. JENSEN
Coloured Petri Nets. In Petri Nets: Applications and Relationships to Other Models of Concurrency Part I, W. Brauer, W. Reisig and G. Rozenberg Eds, Lecture Notes in Computer Science Vol. 254, Springer-Verlag,1985.

[Liskov 93] B. H. LISKOV
A New Definition of the Subtype Relation. In Proc. 7th European Conf. on Object-Oriented Programming, Kaiserlautern (G), Springer-Verlag, 1993.

[May 87] D. MAY
Occam 2 language definition. INMOS Limited, March 1987.

[Matsuoka...93] S. MATSUOKA, A. YONEZAWA
Inheritance anomaly in Object-Oriented Concurrent Programming Languages. In Research Directions in Concurrent Object-Orineted Programming, G. Agha, P. Wegner and A. Yonezawa Eds, MIT Press, 1993.

[Meyer 88] B. MEYER
Object-Oriented Software Construction. Prentice Hall, 1988

[Murata 89] T. MURATA
Petri Nets: Properties, Analysis and Applications; Proc. of the IEEE, vol 77, n° 4, April 1989.

[Mounier 94] J.-L. MOUNIER
The MACAO reference Manual. MASI Laboratory, Paris (F), june 1994.

[Sibertin 85] C. SIBERTIN-BLANC
High Level Petri Nets with Data Structure. In Proceedings of the 6th european Workshop on Application and Theory of Petri Nets; Espoo (Finlande), juin 1985.

[Sibertin 92] C. SIBERTIN-BLANC
A functional semantics for Petri Nets with Objects. Internal Report, University Toulouse 1 (F), October 1992.

[Sibertin 93] C. SIBERTIN-BLANC
A Client-Server Protocol for the Composition of Petri Nets. In Proceedings of the 14th International Conference on Application and Theory of Petri Nets, LNCS 691, Chicago (Il), June 1993.
[Sibertin 94] C. SIBERTIN-BLANC
Communicative and Cooperative Nets. Proceedings of the 15th International Conference on Application and Theory of Petri Nets, Zaragoza (Sp), LNCS 815, Springer-Verlag, 1994.
[Sibertin...95] C. SIBERTIN-BLANC, N. HAMEURLAIN, P. TOUZEAU
SYROCO: A C++ implementation of CoOperative Objects. In Proceedings of the Workshop on Object-Oriented Programming and Models of Concurrency; Turino (I), June 1995.
[Sibertin 97a] C. SIBERTIN-BLANC
Concurrency in CoOperative Objects. In Proceedings of the Second International Workshop on High-Level Parallel Programming Models and Supportive Environments, HIPS'97, Geneva (S), IEEE Society Press, April 1997.
[Sibertin 97b] C. SIBERTIN-BLANC
An overview of SYROCO. In Proceedings of the Tool Presentation Session, 18th International Conference on Application and Theory of Petri Nets, Toulouse (F), June 1997.
[Syroco...96] C. SIBERTIN-BLANC et Al
SYROCO : Reference Manual V7. University Toulouse 1 (F), Oct 1996. © 1995, 97, CNET and University Toulouse 1. SYROCO is available for non commercial use through the site http://www.daimi.aau.dk/PetriNets/tools.
[Wegner 88] P. WEGNER
Inheritance as an Incremental Modification Mechanism, or What Is and Isn't Like. In Proc. ECOOP 88, Oslo (Norway), Springer-Verlag.